OPERATION OF THE PSDF TRANSPORT GASIFIER

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Abstract

The Power Systems Development Facility (PSDF) is an engineering scale demonstration of advanced coal-fired power systems and high-temperature, high-pressure gas filtration systems. The PSDF was designed at sufficient scale so that advanced power systems and components could be tested in an integrated fashion to provide data for commercial scale-up. The PSDF is funded by the U. S. Department of Energy, Electric Power Research Institute, Southern Company, Kellogg Brown & Root, Inc. (KBR), Siemens-Westinghouse, and Peabody Holding Company.

Gasification at the PSDF is based on KBR's Proprietary Transport reactor, which is an advanced circulating fluidized bed reactor designed to operate as either a pressurized combustor or a gasifier. The reactor operates at considerably higher circulation rates, velocities and riser densities compared to a conventional circulating bed. This results in higher throughput, better mixing, and higher mass and heat transfer.

The Transport reactor was operated in combustion mode for approximately 5,000 hours from 1996 - 1999 at a typical operating conditions of 1625°F and 200 psig. The Transport reactor was reconfigured for gasification operations and began operation as a gasifier in September 1999. Over 2,700 hours of gasification was achieved with three different fuels in both air blown and oxygen blown operations. Most of the gasification runs were done with Powder River Basin coal. Gasification was carried out under conditions of 1600 to 1800°F and pressures of up to 250 psig at coal rates of 2,500 to

5,000 pounds per hour. Adiabatic, nitrogen corrected synthesis gas heating values of 80 - 185 Btu/SCF and coal carbon conversions of up to 98% have been achieved. The highest heating values were obtained during oxygen blown operation.

Introduction

The Power Systems Development Facility (PSDF) is an engineering scale demonstration of advanced coal-fired power systems and high-temperature, high-pressure gas filtration systems (PSDF website: "http://psdf.southernco.com/"). The PSDF was designed at sufficient scale so that advanced power systems and components could be tested in an integrated fashion to provide data for commercial scale-up. The PSDF is configured into two separate trains: the Transport reactor train of Kellogg Brown & Root, Inc. (KBR), and the Foster Wheeler Advanced Pressurized Fluidized Bed Combustion (APFBC) system. Both trains contain a Siemens-Westinghouse Particulate Control Device (PCD) which use candle barrier filters to remove particulates. This paper will only discuss the results from the KBR Transport reactor.

A primary focus of the PSDF is to demonstrate and evaluate the Transport reactor and high-temperature, high-pressure particulate collection devices (PCDs), important components required for successful development of advanced power generation systems. The Transport reactor is an advanced circulating fluidized bed reactor designed to operate as either a pressurized combustor or a gasifier. The synthesis gas from the Transport reactor in gasification mode would be used as fuel for a combustion gas turbine, fuel for a fuel cell, or a synthesis gas for chemical processing into chemicals such as methanol or transportation fuels, or a number of other chemicals. The reactor operates at considerably higher circulation rates, velocities and riser densities compared to a conventional circulating bed. This results in higher throughput, better mixing, and higher mass and heat transfer rates.
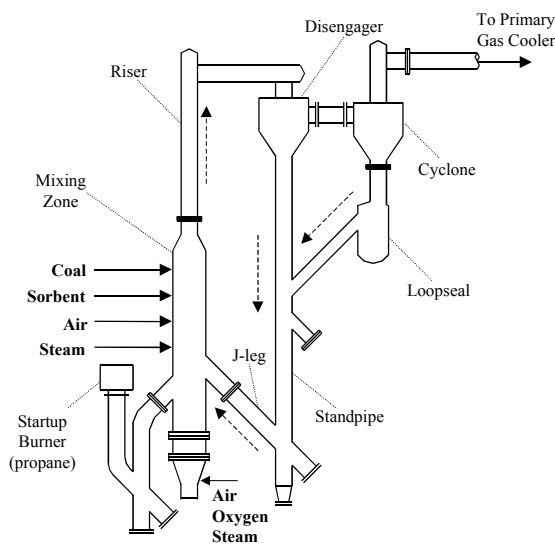
Process Description

Figure 1 - Transport Reactor

The Transport reactor operating in gasification mode consists of a mixing zone, a riser, a disengager, a cyclone, a standpipe, a dipleg, and a J-leg. A schematic of the Transport reactor is shown in Figure 1. The fuel, sorbent, steam, and air are routed separately and mixed together in the mixing zone, along with the solids from the standpipe. The mixing zone, located below the riser, has a slightly larger diameter compared to the riser. The gas and solids move up the riser together, make two turns and enter the disengager. The disengager removes larger particles by gravity separation. The gas and remaining solids then move to the

cyclone, which removes most of the particles not collected by the disengager. The gas then exits the Transport reactor and goes to the primary gas cooler and the PCD for final particulate clean-up. The solids collected by the disengager and cyclone are recycled back to the reactor mixing zone through the standpipe and a J-leg. The nominal Transport reactor operating temperature is 1,800°F for gasification mode. The reactor system is designed to have a maximum operation pressure of 294 psig with a thermal input capacity of about 41 million Btu/hr.

Figure 2 is a process flow diagram of the Transport reactor system, including the feed, waste solids, and gas systems. The fuel and sorbent are separately fed into the Transport
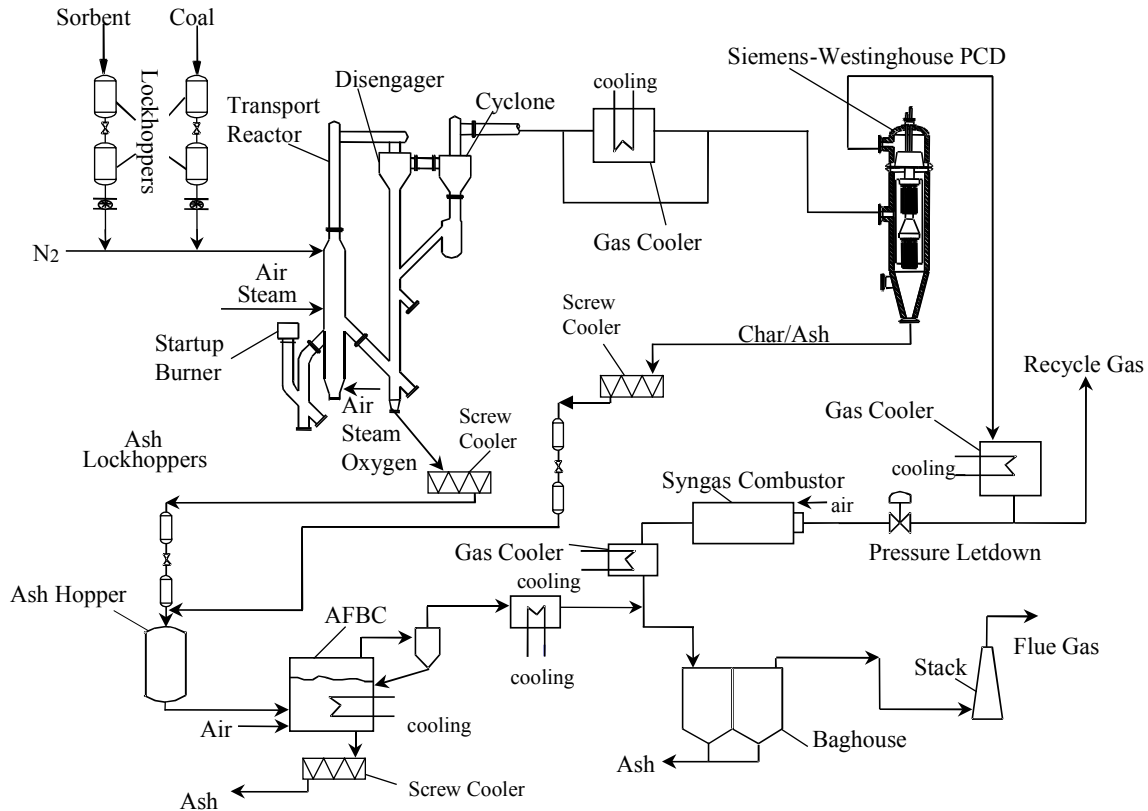

Figure 2 - Transport Reactor System

reactor through lockhoppers. The gas leaves the Transport reactor cyclone and goes to the primary gas cooler which cools the gas prior to entering the Siemens-Westinghouse PCD barrier filter. The filter uses ceramic or metal candles to filter out dust from the reactor. The filter removes almost all the dust from the gas stream (to less than 1 ppm) to prevent erosion of a downstream gas turbine in a commercial plant. The operating temperature of the filter is controlled both by the reactor temperature and by an upstream gas cooler. For test purposes, the gas from the Transport reactor can flow through the gas cooler from zero to 100 percent. The PCD gas temperature can range from 700 to 1,600°F. The filter candles are back-pulsed by high-pressure nitrogen in a desired time interval or at a given maximum pressure difference across the candles. There is a secondary gas cooler after the filter vessel, to cool the gas before discharging to the syngas combustor. In a commercial plant, the gas from the PCD would be sent to a

combustion gas turbine, a fuel cell, or used as a chemical feedstock. The synthesis gas is sampled for on-line analysis both before and after the secondary gas cooler.

After exiting the secondary gas cooler, the gas is letdown to about 2 psig through a pressure control valve. The synthesis gas is then sent to a syngas combustor to burn the gas and oxidize all reduced sulfur compounds (H_2S, COS, CS_2) and reduced nitrogen compounds (NH_3, HCN). The syngas combustor uses a small amount of propane as a backup fuel which would be ramped up to maintain plant steam conditions in case of a Transport reactor upset or trip. The gas from the syngas combustor combines with the gas from the atmospheric fluidized bed combustor (AFBC) and goes to the baghouse and then to the stack.

The Transport reactor produces fine ash collected by the PCD and coarse ash extracted from the Transport reactor standpipe. The two solid streams are cooled using screw coolers, reduced in pressure in lock hoppers and then combined together. Any fuel sulfur captured by sorbent is present as calcium sulfide (CaS) in the ash which is not suitable for landfill. The gasification ash is processed in an AFBC to oxidize the CaS to calcium sulfate ($CaSO_4$) and burn the residual carbon in the ash. The waste solids are then suitable for commercial use or disposal. The AFBC recovers the PCD solids carbon heat content as superheated steam.

Combustion

The Transport reactor operated in combustion mode for approximately 5,000 hours from 1997 - 1999 at a typical operating condition of 1625°F and 200 psig. Combustion heat was removed using a solids cooler (not shown on Figures 1 & 2). Fuels used include three bituminous coals from Alabama, East Kentucky and Illinois, a sub-bituminous coal from the Powder River Basin (PRB) in Wyoming, and petroleum coke from a Alabama refinery. Stable operations were demonstrated for all fuels and sorbents tested[1,2].

Gasification

The Transport reactor was reconfigured as a gasifier by removing the solids cooler from service and commissioning the AFBC and syngas combustor. The following gasification tests have been performed, with the mode of operation, coals used, and hours in gasification:

- GCT1 - Air, PRB, Alabama bituminous, Illinois #6, September - December 1999, 233 hours
- GCT2 - Air, PRB, April 2000, 217 hours
- GCT3 - Air, PRB, January 2001, 183 hours
- GCT4 - Air, PRB, March 2001, 242 hours
- TC06 - Air, PRB, July - September 2001, 1,025 hours
- TC07 - Air, PRB, Alabama bituminous, January - April 2002, 442 hours
- TC08 - Air, oxygen, PRB, June 2002, 364 hours.

During the outage between GCT2 and GCT3, a loop seal was installed to the cyclone dipleg to improve the stability of the reactor during PCD back pulses. Improvements were also made to the cyclone and disengager to improve particulate collection. During the outage between TC06 and TC07, an addition to the mixing zone was added so that oxygen could be added to the reactor.

Test results for GCT1, GCT2, GCT3, and GGCT4 have been given in two previous papers[3,4]. This paper will cover the results of TC06 and preliminary results of TC07 and TC08.

Gasification Operations

Prior to TC06, a number of process improvements were made to the Transport reactor system. The two most important were to prepare a separate feeder to supply the Transport reactor with coke breeze during startup and reactor trips and to create a temperature control loop for the Transport reactor that made fine adjustments to the air feed rate to control the Transport reactor temperature. TC06 began on July 4, 2001, with coal feed commencing on July 11. On July 18, the temperature control loop was placed in service for the first time. The period from July 11 until July 24 was plagued with problems caused by main air compressor surges. On July 24 the Transport reactor was shut down to tune the compressor. During the course of the tuning, a char bridge in the PCD ignited and damaged a few candles.

After a four-week outage, the test campaign continued on August 19, 2001. Over the next three weeks, the main problem affecting the Transport reactor was periodic short trips caused by difficulties experienced by the coal feed lock hopper when trying to feed coal with a higher than normal percentage of fines. On September 12, a change in the coal processing procedure was made. Up until this point, the pulverized coal silo would be filled and then the level would be allowed to decline as coal was sent to the coal feeder before the mill would be restarted and the silo refilled. During the periods of low silo levels, an increased fraction of the coal sent to the coal feeder would consist of fines. The new procedure called for operating the coal mill continuously, maintaining a constant level in the pulverized silo. The new procedure virtually eliminated coal feeder problems for the rest of the run and has continued to be used in subsequent test runs. From September 13 until the end of the test run on September 27, the unit ran with only one short coal feeder trip and no other trips caused by operational problems.

During TC06, the Transport reactor operated for 1,025 hours on PRB coal. The Transport reactor was operated at pressures from 190 to 230 psig and at temperatures of 1725 to 1825ºF. The addition of the coke breeze feeder greatly improved operations. During startup, the coke breeze was used to heat the Transport reactor from about 1200ºF to about 1700ºF before starting coal feed. This eliminated the formation of tar that is experienced when starting coal feed at 1200ºF. The tar produced during startup would plug the gas analyzers and increase the baseline pressure drop of the particulate collection device. TC06 had the highest availability of the gas analyzers compared to any previous gasification test. The temperature control loop performed very well and led to more

stable Transport reactor operation. Upon inspection after the run, a leak in the primary gas cooler was found.

It was decided to replace the cooler's tube bundle in the outage before TC07. This outage also saw a major modification to the lower mixing zone to add a spool piece and associated piping to allow for the addition of oxygen to the Transport reactor. In December 2001, TC07 started with a refractory cure in the new lower mixing zone (LMZ) and sand circulation tests at low temperatures to commission the LMZ and see if there would be a major effect on the fluidization characteristics of the Transport reactor. No problems were found. In early January the new tube bundle for the primary gas cooler was installed and TC07 continued. The major goal for TC07 was the commissioning of the LMZ on air with both PRB and an Alabama bituminous coal to prepare for oxygen blown operation. PRB coal feed was established on January 19, 2002. After 102 hours on PRB, the Transport reactor was transitioned to bituminous coal on January 25. The bituminous coal was fed for 34 hours before a loss of circulation in the Transport reactor led to a reactor shutdown. An inspection revealed large deposits in the mixing zone and LMZ.

After a short outage, coal feed using Alabama bituminous coal was started on February 7. Almost immediately, there were indications of deposits forming in the mixing zone. After ten hours, coal feed was discontinued because of a loss of circulation in the Transport reactor and particles penetrating the PCD. Upon inspection, the mixing zone and LMZ were again found to be plugged with solids. In addition, a thermowell in the LMZ was found melted and the thermocouples in the LMZ were found to have only been partially inserted leading to much higher operating temperatures than indicated by the instruments. TC07 coal feed was restarted on March 23 as an air blown PRB test run to complete the LMZ commissioning. During this outage, the superheated steam piping to the lower mixing zone was rerouted to reduce heat loss and condensation. The Transport reactor was then operated for 296 hours on PRB. The LMZ temperature and pressure profiles were acceptable over a wide range of air and steam flows. An inspection after the run did not find any deposits but did find that the primary gas cooler ferrules, made of 310SS, had been eroded and corroded. These were replaced with ceramic ferrules in the outage following TC07. During TC07, the Transport reactor was operated at temperatures from 1670 to 1820°F and pressures of 190 to 220 psig.

The Transport reactor was placed into oxygen blown operation for the first time during TC08. TC08 started on June 5, 2002, and coal feed commenced on June 11. The Transport reactor operated on PRB coal in air blown mode for about 70 hours before transitioning to enriched air operation on June 14. Due to limitations in the oxygen delivery system, oxygen was always added at less than 160 psig reactor pressure. After steadily increasing the percentage enriched air to the Transport reactor, operation on full oxygen started on June 17. The reactor tripped four times during initial operation when a pressure tap became repeatedly plugged causing the coal feeder to trip. After restarting, the Transport reactor ran in oxygen blown mode until June 26 when the unit entered a short, 8-hour, planned outage to make a minor modification to sample the alkali emissions after the PCD. The remainder of the run was in air blown mode. There was a

total of 364 hours of coal feed in TC08 broken down into 156 hours of air blown, 56 hours of enriched air (15 to 85% air enrichment), and 152 hours of oxygen blown operation. The oxygen blown operation was a successful commissioning of the LMZ and demonstrated stable operations on oxygen with high syngas lower heating values, and without hotspots in the Transport reactor.

Reactor Performance

A summary of the operating conditions in the gasification tests conducted thus far can be found in Table 1.

The circulation rate of the Transport reactor is most closely influenced by the level of solids in the standpipe. The aeration to the j-leg has a lesser effect. The circulation rate is calculated from the riser differential pressure measurement and riser gas velocity. The effect of increases in standpipe level on the riser differential pressure is shown in Figure 3. Figure 4 shows the effect of standpipe level on the pressure drop across the gasifier
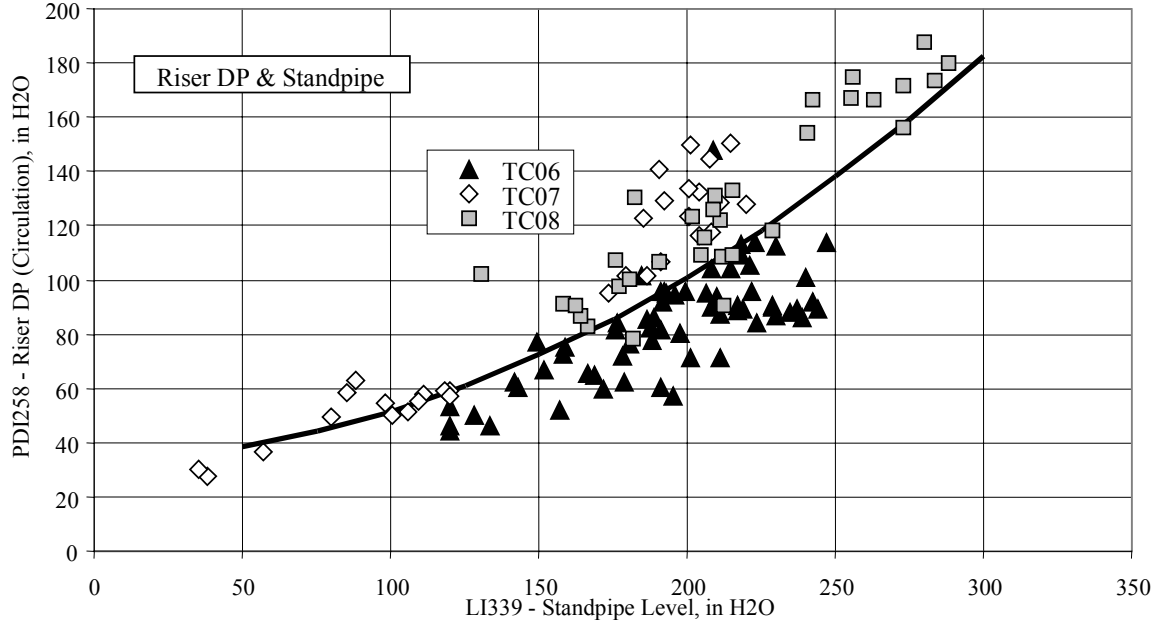

Figure 3 -Riser Pressure Drop & Standpipe Level

loop. There is not a strong connection between the aeration to the reactor j-leg and the circulation rate. The circulation rate of solids in the gasifier is very high corresponding to a mass flux of up to 700 pounds / second-ft^2. High solids circulation rates resulted in uniform temperatures around the gasifier loop, improving the thermal cracking capability of devolatized products in the riser. No tar was observed in the product syngas.
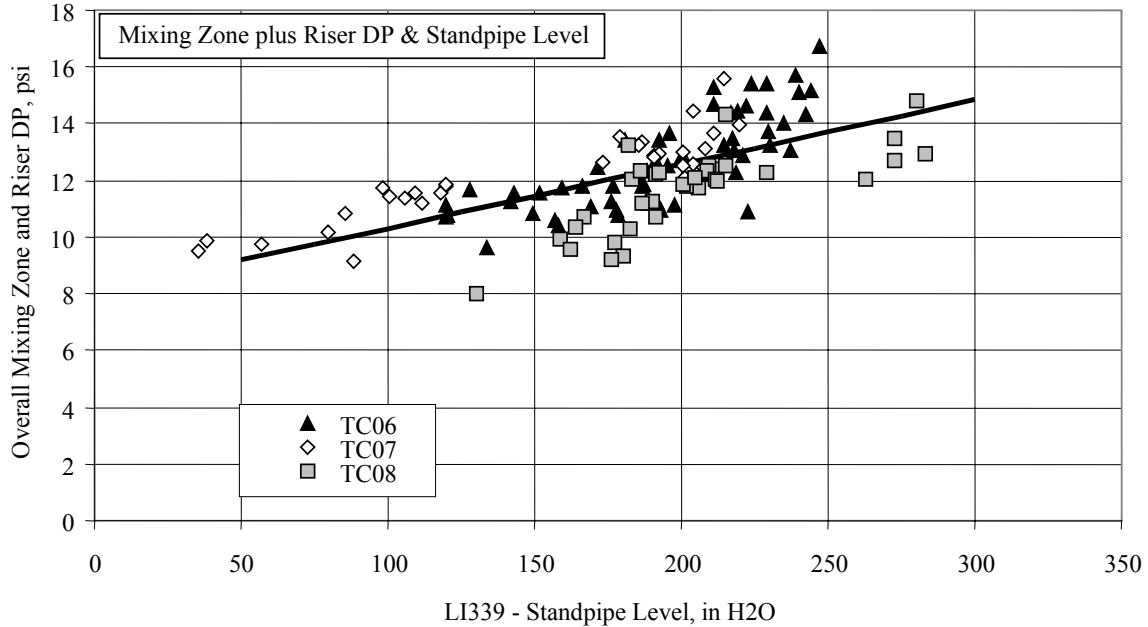
Figure 4 -Mixing Zone + Riser Pressure Drop & Standpipe Level

Gasification Results

The Transport reactor was operated on Powder River Basin coal for all of TC06 and TC08. During TC07, the reactor was operated on Alabama bituminous coal, but steady conditions could not be obtained due to improper installation of thermocouples. All the results in this section will be for PRB coal operation. The average PRB coal analyses for TC06 testing is given in Table 2.

The synthesis gas lower heating value is the primary criteria on how well the gasification process is performing if the ultimate goal is for Integrated Gasification Combined Cycle (IGCC) power generation. A typical goal for IGCC service is a LHV of 110 Btu/SCF. Synthesis gas is sampled and analyzed after the PCD for H_2, CO, CO_2, N_2, CH_4, C_2^+, and H_2O. The synthesis gas LHV is determined from the gas composition using the formula:

$$LHV(Btu/SCF) = \left\{ \begin{array}{l} 275 \times (H_2\%) + 322 \times (CO\%) + \\ 913 \times (CH_4\%) + 1641 \times (C_2H_6^+\%) \end{array} \right\} / 100 \qquad (1)$$

A way to compare the results of both oxygen and air blown run is to use the overall percent of oxygen of all gas that is fed to the Transport reactor. The overall $\%O_2$ is calculated by dividing the sum of the air oxygen and the pure oxygen flow rates by the sum of the air, steam, pure oxygen, and pure nitrogen flow rates. (The flow rates are in moles per hour.) A large amount of pure nitrogen is fed to the reactor for instrument purges, coal and sorbent transport, and equipment purges. In air blown operation, about 50% of the synthesis gas nitrogen comes from air and 50% comes from the nitrogen supply system. The raw LHV is plotted against overall percent oxygen in the feed gases

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on Figure 5. Raw data from 11 to 15% overall O_2 in the feed gas is from air blown operation. Raw data from 17 to 19% overall O_2 is from a combination of air-blown and
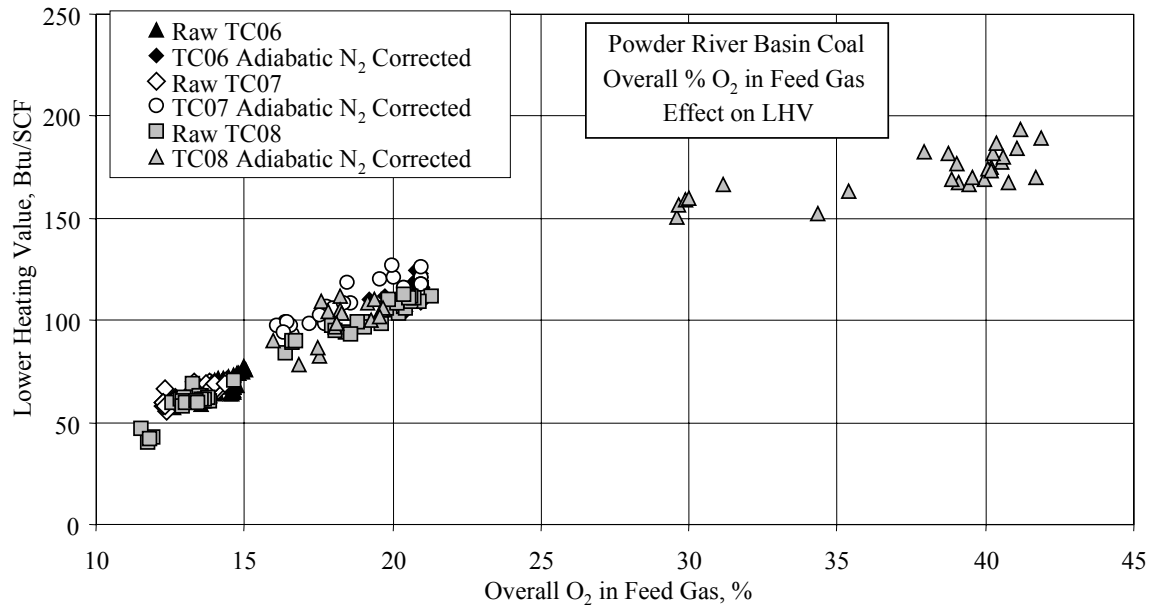

Figure 5 - Synthesis Gas Lower Heating Value

oxygen-blown operations. Raw data from 19 to 21 overall $\%O_2$ is from full oxygen-blown operation. The raw LHV increases from about 50 Btu/SCF at 12 overall $\%O_2$ to about 110 Btu/SCF at 20.5 overall $\%O_2$. The raw LHV increases with increasing overall $\%O_2$ due to a decrease in the amount of nitrogen from air that is diluting the synthesis gas.

A commercial-sized plant would have a lower relative nitrogen usage compared to the PSDF Transport reactor. There would be minimal nitrogen usage in a commercial plant because the PSDF demonstration Transport reactor nitrogen would be replaced by recycled synthesis gas. A commercial plant would also have a lower heat loss per pound of coal gasified than the PSDF due to the PSDF Transport reactor's higher surface area to volume ratio compared to a commercial reactor. To estimate the LHV of a commercial plant, the measured synthesis PSDF gas LHV is corrected for reactor heat loss and the effect of additional nitrogen. This correction has been applied to the LHV measured in TC06, TC07, and TC08 and is shown in Figure 5. The adiabatic, nitrogen corrected values were from 100 Btu/SCF at 17 overall $\%O_2$ to 194 Btu/SCF at 42 overall $\%O_2$.

When the Transport reactor is operated in air blown operation with no steam addition and when all the additional nitrogen (non-air nitrogen) has been replaced with recycle gas, the overall $\%O_2$ will be 21%. The data from the oxygen-blown operation and the air blown operation (adiabatic nitrogen corrected) both agree that the LHV will be at about 100 - 120 Btu/SCF at 21% overall O_2. Essentially, it is assumed that the removal of nitrogen from air has the same effect as the removal of added nitrogen. When the Transport reactor is operated in oxygen blown mode, with all the additional nitrogen replaced by synthesis gas (0.0% N_2 in the synthesis gas), and the steam to oxygen rate is about 0.8

pound oxygen to pound steam, the overall O_2% will be 42%. Additional increases in LHV can only be achieved by decreasing the steam rate.

Carbon conversion is defined as the amount of coal carbon that is gasified. The remaining solids carbon leaves the Transport reactor either with the PCD fines or with the coarse reactor solids. The PCD solids typically have 20 to 40% carbon (3,000 to 5,500 Btu/pound) and can be burned in a conventional combustor to recover the heating value. In an IGCC plant, the heating value of the carbon in the spent solids is not wasted, but is recovered in a less efficient process compared to the IGCC gas turbine. The carbon conversions for TC06, TC07, and TC08 are given in Figure 6 as a function of reactor
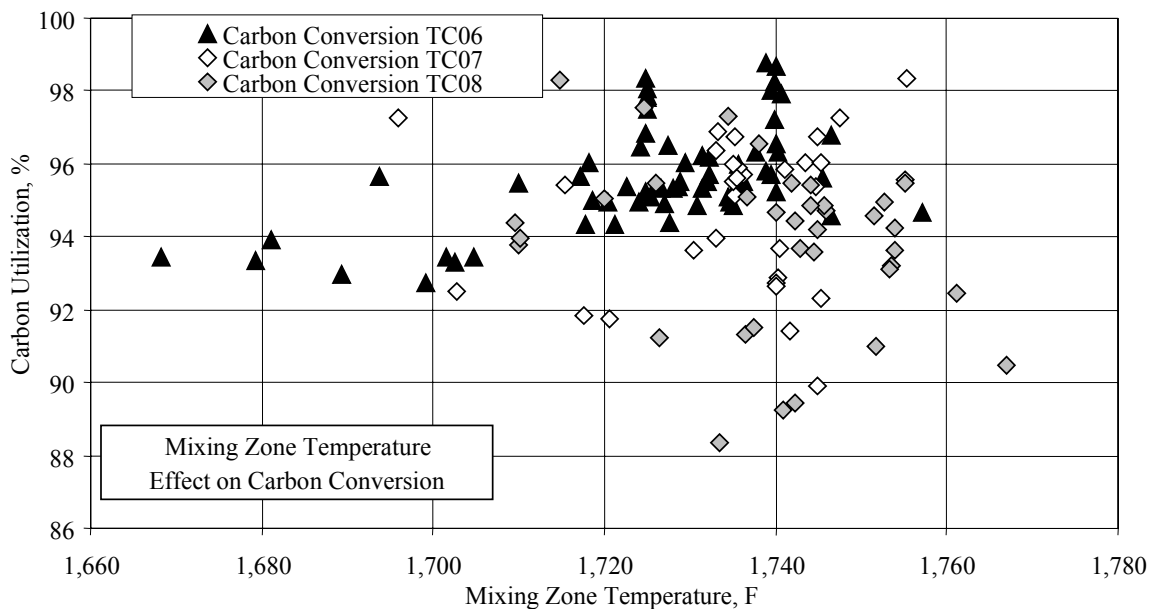

Figure 6 - Carbon Conversion

mixing zone temperature. For all conditions, carbon conversions are quite good, above 88%, with an average carbon conversion of about 95%. Carbon conversion should increase as mixing zone temperature increases. For TC06, the carbon conversion definitely increases as mixing zone temperature increases. For TC07, the carbon conversion does not show a real trend with mixing zone temperature, possibly due to the narrow band of mixing zone temperatures tested. For TC08, the carbon conversion slightly decreases with mixing zone temperature, which may be misleading due to the preliminary nature of the TC08 carbon conversion data.

The hourly TC08 raw LHV and carbon conversion data for the first 300 hours is plotted against run time on Figure 7. The overall %O_2 in the feed gas is plotted to show the relative amount of pure oxygen that replaces gasification oxygen from air. The times of unit trips are also shown on Figure 7. There was also some minor coal feeder trips in the 300-hour time period that were not flagged out on Figure 7, but can be noted by gaps in the data or low LHV. At hour 60, the pressure was reduced from 220 to 140 psig and the coal feed rate was reduced by about 1,000 pounds per hour. The LHV decreased since the nitrogen rate remained constant, while the air and synthesis gas rates decreased, diluting the synthesis gas. Oxygen was added to enrich air for four hours and the LHV
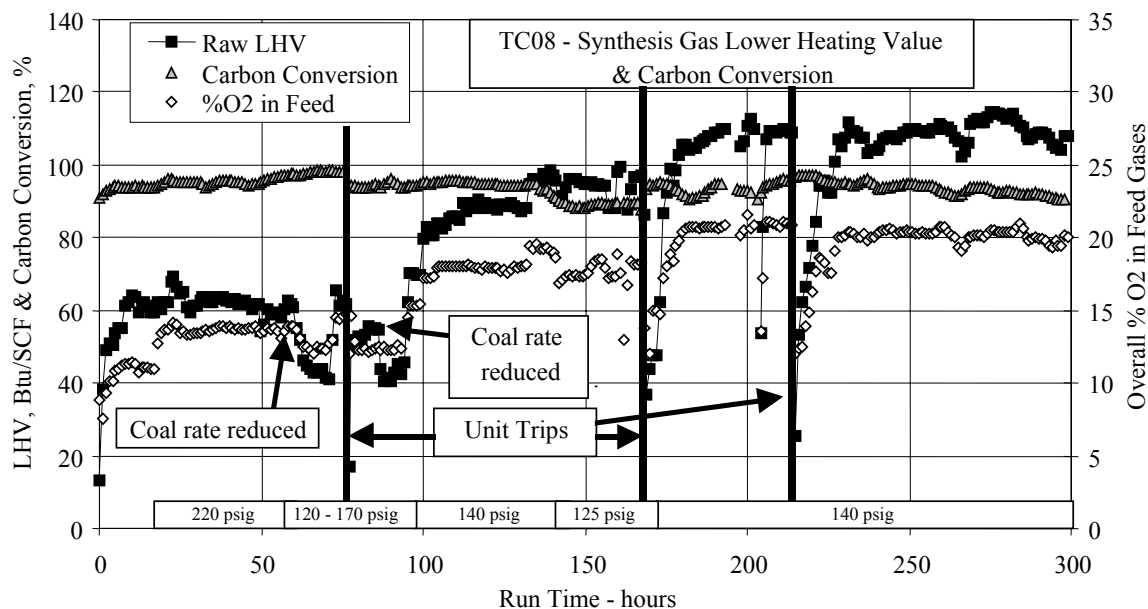
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Figure 7 - TC08 LHV & Carbon Conversion

increased from 45 to 60 Btu/SCF before the unit tripped at hour 76. The coal rate was decreased by about 800 pounds per hour at hour 86 in air-blown operation and the LHV again decreased due to dilution. The second addition of oxygen to enrich air further was at hour 96 when the LHV increased from 45 to 100 Btu/SCF while the overall $\%O_2$ increased from 12 $\%O_2$ to 18 $\%O_2$. This period was an enriched air testing period when both air and oxygen were added to the Transport reactor. At hour 181 full oxygen blown operation was achieved at nearly 21 overall $\%O_2$ and 105 Btu/SCF. From hour 181 to hour 300 the unit was operated in oxygen-blown mode, except when recovering from trips. The LHV was constant from hour 181 to hour 300 at about 104 to 114 Btu/SCF, while the overall $\%O_2$ was constant at about 20 overall $\%O_2$. Note the several successful transitions from air blown to oxygen blown operation.

The carbon conversion was excellent for the first 76 hours of air-blown TC08, gradually increasing to nearly 98%. During the enriched air tests from hour 100 to hour 168 and the full oxygen blown tests from hour 218 to 300, the carbon conversions decreased from 95 to 90%. During TC08, only small amounts of solids were removed from the standpipe and typically the solids contained very little carbon. The carbon conversion is a function of the PCD fines and carbon content of the PCD fines, both of which changed very slowly during TC08.

The Transport reactor typically begins a run charged with about 6,000 pounds of 112-micron mass mean diameter (MMD) sand. The Transport reactor solids are circulating very fast and to which 350-micron MMD coal and 10-micron MMD limestone are injected into the mixing zone at about 1750ºF. The reactor produces mostly fine char at about 15 microns MMD with smaller amounts larger particles. During TC06, the reactor solids slowly increased to about 150 microns MMD as the start-up sand was replaced by coal ash and limestone. The change in Transport reactor solids composition is shown in Figure 8 which plots reactor weight percent SiO_2, CaO, and Al_2O_3 in the circulating solids against run time. As TC06 progressed, the SiO_2 decreased and the CaO and Al_2O_3
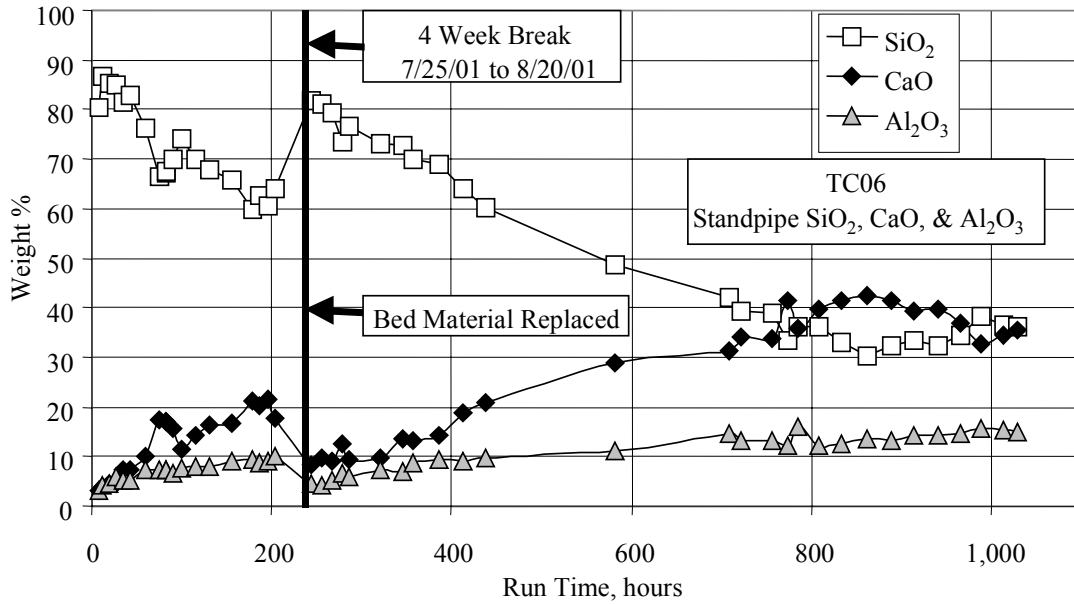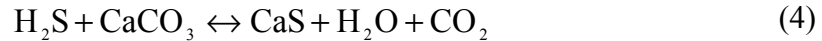
Figure 8 - Standpipe SiO_2. CaO, & Al_2O_3

increased as the startup sand was replaced with compounds from the coal ash and limestone. The reactor was shut down after 220 hours of operation for four weeks in the middle of TC06 and the bed material was drained out. After the bed material was replaced, it took another 550 hours (at hour 770) for the reactor solids to reach a constant value. During this period, the coal rate was about 4,500 pounds per hour, the coarse reactor solids were withdrawn at about 80 pounds per hour and the fine PCD char rate was about 400 pounds per hour. The length of time that it takes the reactor to reach a constant composition is a function of the reactor solids withdrawal rate and the rate of attrition of the reactor solids that then exit with the PCD char.

The equilibrium H_2S concentration in coal gasification using limestone is governed by three reversible reactions:

$$CaCO_3 \leftrightarrow CaO + CO_2 \tag{2}$$

$$H_2S + CaO \leftrightarrow CaS + H_2O \tag{3}$$

$$H_2S + CaCO_3 \leftrightarrow CaS + H_2O + CO_2 \tag{4}$$

Reaction (2) is the limestone calcination reaction. At thermodynamic equilibrium, the CO_2 partial pressure should be a function of only the system temperature as long as there are both $CaCO_3$ and CaO present according to the equilibrium constant:

$$K_1 = P_{CO_2}^O \tag{5}$$

where P^O_{CO2} is the partial pressure of CO_2.

The H_2S equilibrium is governed by reactions (3) and (4), with the associated equilibrium constants:

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$$K_2 = \frac{P^O_{H_2O}}{P^O_{H_2S}} \tag{6}$$

$$K_3 = \frac{P^O_{H_2O} P^O_{CO_2}}{P^O_{H_2S}} \tag{7}$$

Equations (5) - (7) state that the equilibrium H_2S concentrations in the $CaCO_3$-CaO-CaS system is a function of the system temperature and the CO_2 and H_2O partial pressures. As the CO_2 and H_2O partial pressures increase, so would H_2S partial pressures. The equilibrium constants are all functions of temperature and can be determined using thermodynamic data. A more detailed description of the H_2S equilibrium calculations is given the GCT1 Final Report[5].

The Transport reactor H_2S analyzer was not working during TC06 and was not very reliable during TC07 and TC08, so the H_2S concentration and sulfur emissions from the transport reactor were not directly measured. The synthesis gas combustor SO_2 analyzer operated well during all test runs and measures the total sulfur emissions from the Transport reactor. The total sulfur emissions consists of H_2S, COS, and CS_2. The main sulfur species in coal gasification are considered to be H_2S and carbon oxysulfide (COS). There should also be only a minor amount of carbon disulfide (CS_2).

The minimum thermodynamic H_2S concentrations were calculated from the measured partial pressures of CO_2 and H_2O. The measured total reduced sulfur (TRS) and minimum H_2S concentrations are compared in Figure 9. The comparison between
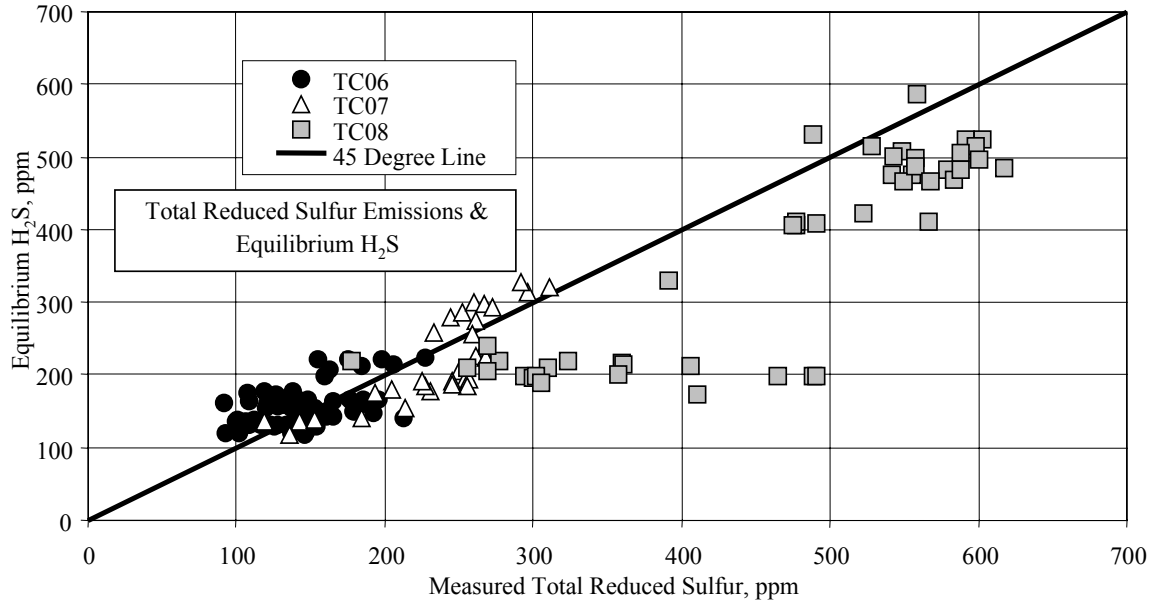

Figure 9 - Measured Total Reduced Sulfur & Equilibrium H_2S

measured and minimum equilibrium H_2S concentrations is quite good for TC06 and TC07 which had measured total reduced sulfur emissions of less than 300 ppm. TC08 had TRS emissions greater than the equilibrium H_2S emissions, possibly because at

higher TRS emissions there were significant COS and CS_2 emissions. All the data is from PRB coal operation with a coal sulfur content of about 0.25% during both air and oxygen blown operation. The wide range of H_2S emissions is due to the varying steam feed rates and resulting high variations in synthesis gas H_2O concentrations (6% to 25% H_2O). This equilibrium control of H_2S emissions in TC06 & TC07 indicated that sufficient CaO or $CaCO_3$ had been fed to the reactor and the H_2S removal was not limited by the amount of limestone fed to the reactor.

During TC06 and TC07 the limestone feed rate was selected to give a calcium to sulfur ratio of about 2.0. For several periods of up to 8 hours, the limestone feed was turned off and the H_2S emissions did not change. Powder River Basin coal is a low sulfur, high alkaline coal with a Ca/S ratio of 2.8 indicating that there is a large excess of calcium, which can react with the coal sulfur, even without any limestone addition. In both dry and wet scrubbing, it has been possible to use the alkalinity of an alkaline ash coal for SO_2 removal.

To determine whether PRB coal ash alkalinity is effective as limestone in H_2S control, limestone was not added to the Transport reactor during TC08, so the only source of alkalinity was from the PRB coal ash. The TC08 hourly total reduced sulfur (TRS) and the equilibrium H_2S concentrations (calculated for times when the synthesis gas CO_2 and H_2O partial pressures were constant) were plotted against time in Figure 10. For the first
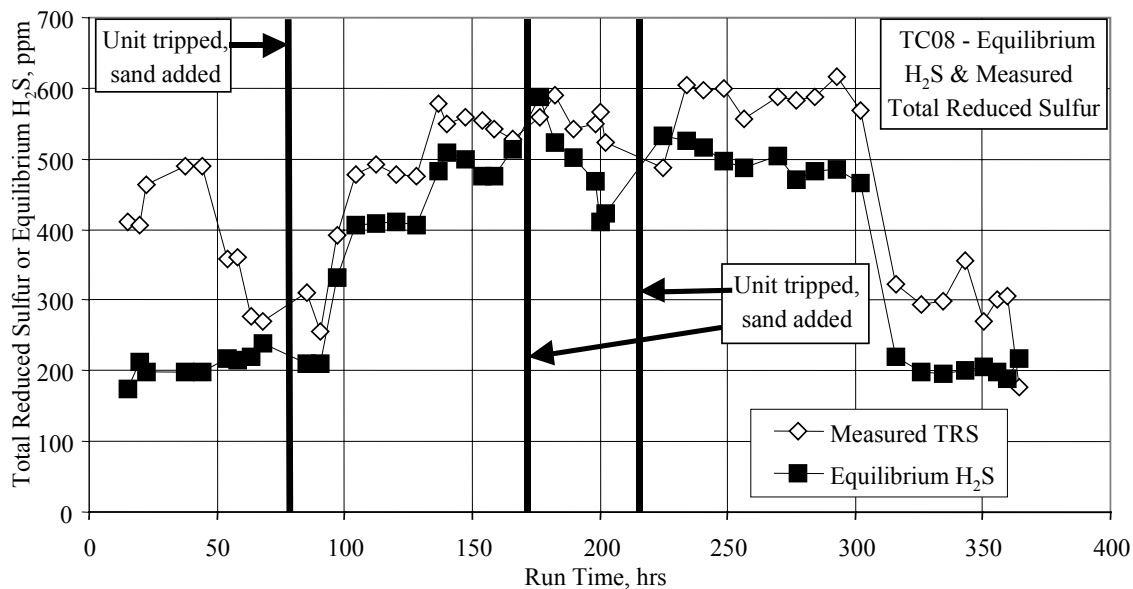

Figure 10 - TC08 Measured Total Reduced Sulfur & Equilibrium H_2S

45 hours of TC08, the TRS emissions increased to 500 ppm and were much higher than the equilibrium H_2S concentration of 200 ppm. From hour 45 to hour 68, the measured TRS then decreased from 500 ppm down to 270 ppm, close to the equilibrium value of 240 ppm. After hour 68, the equilibrium H_2S was about 100 ppm lower than the measured TRS. This was despite that some reactor trips typically cause the loss of reactor solids containing coal ash alkalinity. Sand was added to the reactor after a trip to makeup the lost reactor solids. One interpretation of this data is that for H_2S removal

there must be a certain quantity of alkalinity in the reactor circulating solids to achieve 100 ppm above equilibrium H_2S emissions. It took about 68 hours at the TC08 coal rates to achieve the required alkalinity in the reactor solids. Reactor solids samples were taken from the standpipe during TC08 and will be analyzed for the typical coal ash constituents. It is expected that the reactor solids CaO content will be the controlling factor that determines whether the Transport reactor can achieve near equilibrium H_2S emissions. The TC08 results indicate that the PRB coal alkalinity is sufficient to achieve nearly as much H_2S removal as the addition of limestone. Hence, minimal limestone feed is required for PRB operation.

The lower equilibrium H_2S emissions were during air blown operation when minimal steam was added to the reactor. During oxygen blown operation, a higher steam rate was used to control reactor temperature and a lower reactor pressure was used due to the oxygen feed system. Both effects resulted in a higher H_2O partial pressure and higher H_2S emissions.

The TC06 ammonia and hydrogen cyanide emissions were measured by extractive sampling. The TC06 NH_3 emissions were from 1,300 to 1,900 ppm and the HCN emissions were from 40 to 70 ppm. A continuous NH_3 analyzer was installed for TC07 and the NH_3 emissions were from 1,700 to 1,900 ppm. About 80 to 90% of the fuel nitrogen was converted to NH_3. The TC08 air blown NH_3 emissions were comparable to the TC06 and TC07 NH_3 emissions.

Conclusions

Gas heating values and carbon conversions met the commercial goals for the PRB coal. Sulfur emissions were as predicted from thermodynamic equilibrium at low sulfur emissions. The Powder River Basin coal ash alkalinity was nearly sufficient to remove the equilibrium amount of synthesis gas sulfur. The Transport reactor could be operated for 800 hours continuously with only one coal feeder if a coke breeze feed system was available to cover for any coal feeder trips. The oxygen delivery and new lower mixing zone operated well, permitting stable Transport reactor operation on both enriched air and full oxygen-blown service.

Future Activities

Future tests will focus on testing additional coals in both air and oxygen blown modes. The next test is planned for bituminous coal feed. The Transport reactor synthesis gas stream will be connected to a modified gas combustor and an existing gas turbine to generate power. Recycle gas will be substituted for aeration nitrogen to increase the LHV. A fluidized coal feeder will be installed and tested as a backup to the present coal feed system

Acknowledgements

References

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Table 1 TC06, TC07, & TC08 Operating Conditions
(Air Blown Operations)

Fuel Type	Powder River Basin, Alabama Calumet Bituminous
Fuel Particle Size (mmd)	200 - 350 μm
Average Fuel Feed Rate, pph	2,700 - 5,000
Sorbent Type	Ohio Bucyrus limestone
Sorbent Particle Size (mmd)	10 - 30 μm
Sorbent Feed Rate	0 - 200 pph
Reactor Temperature, $^{\circ}$F	1670 - 1825
Reactor Pressure, psig	140 - 240
Riser Gas Velocity, fps	40 – 60
Riser Mass Flux, lb/s·ft^2	150 - 700
Standpipe Level, in. H_2O (LI339)	150 - 300
Synthesis Gas Flowrate, pph	15,000 - 30,000
Air/coal ratio	2.5 – 3.5
Steam/coal mass ratio	0.0 to 1.0

Table 2 TC06 PRB Coal Analyses

	Value	Standard Deviation
Moisture, wt%	20.93	1.08
Carbon, wt%	57.02	1.04
Hydrogen, wt%	3.74	0.12
Nitrogen, wt%	0.66	0.05
Sulfur, wt%	0.26	0.02
Ash, wt%	5.23	0.45
Volatiles, wt%	37.39	8.83
Fixed Carbon, wt%	36.46	9.44
Higher Heating Value, Btu/lb	9,391	129
Lower Heating Value, Btu/lb	8,828	133
CaO, wt %	1.27	0.13
SiO_2, wt %	1.66	0.24
Al_2O_3, wt %	0.88	0.10
MgO, wt %	0.28	0.02
Fe_2O_3, wt %	0.33	0.06
Ca/S, mole/mole	2.83	0.29